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A multiscale model of distributed fracture and permeability in solids in all-round compression

Maria Laura De Bellis[a], Gabriele Della Vecchia[b], Michael Ortiz[c], Anna Pandolfi[b,*]

[a] DII, Università del Salento, 73100 Lecce, Italy
[b] DICA, Politecnico di Milano, 20133 Milano, Italy
[c] EAS, Caltech, Pasadena CA 91125, USA

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ABSTRACT

We present a microstructural model of permeability in fractured solids, where the fractures are described in terms of recursive families of parallel, equidistant cohesive faults. Faults originate upon the attainment of tensile or shear strength in the undamaged material. Secondary faults may form in a hierarchical organization, creating a complex network of connected fractures that modify the permeability of the solid. The undamaged solid may possess initial porosity and permeability. The particular geometry of the superposed micro-faults lends itself to an explicit analytical quantification of the porosity and permeability of the damaged material. The model is the finite kinematics version of a recently proposed porous material model, applied with success to the simulation of laboratory tests and excavation problems [De Bellis, M. L., Della Vecchia, G., Ortiz, M., Pandolfi, A., 2016. A linearized porous brittle damage material model with distributed frictional-cohesive faults. Engineering Geology 215, 10–24. Cited By 0. 10.1016/j.enggeo.2016.10.010]. The extension adds over and above the linearized kinematics version for problems characterized by large deformations localized in narrow zones, while the remainder of the solid undergoes small deformations, as typically observed in soil and rock mechanics problems. The approach is particularly appealing as a means of modeling a wide scope of engineering problems, ranging from the prevention of water or gas outburst into underground mines, to the prediction of the integrity of reservoirs for CO_2 sequestration or hazardous waste storage, to hydraulic fracturing processes.

1. Introduction

Damage induced by mechanical or hydraulic perturbations influences the permeability of the rock mass, with significant effects on the pore pressure distribution. Modifications in the pore pressure, in turn, affect the mechanical response of the material by poromechanical coupling. According to experimental observations at the microscopic scale, fracture evolution in rocks can be interpreted essentially as a progressive damage accumulation process, characterized by nucleation, growth and coalescence of numerous cracks following changes in the external load or in the internal pore pressure (Kranz, 1983; Wong et al., 1996). In the particular case of hydraulic fracturing, a stimulation technique used in petroleum industry to increase

* Corresponding author.
E-mail address: anna.pandolfi@polimi.it (A. Pandolfi).

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the oil/gas production in low permeability reservoirs, fractures are produced by the artificial increase of the fluid pressure in a borehole. From the theoretical point of view, it has been observed that the success of hydraulic fracturing is related to: i) the creation of a dense system of hydraulic cracks with limited spacing; and ii) the prevention or mitigation of localization instabilities (Bažant et al., 2014).

Models of distributed damage and permeability based on abstract damage mechanics are, of necessity, empirical in nature and the precise meaning and geometry of the damage variables often remains undefined or is associated with unrealistic microstructures such as distributions of isolated microcracks. In addition, the evolution of the damage variables and their relation to the deformation, stress and permeability of the rock mass are described by means of empirical and phenomenological laws that represent, at best, enlightened data fits. However, the permeability enhancement due to extensive fracturing of a rock mass depends sensitively on precise details of the topology, which needs to be *connected*, and geometry of the crack set, including the orientation and spacing of the cracks. In addition, the coupled hydro-mechanical response of the rock, especially when complex loading conditions and histories are of concern, is much too complex to yield to empirical data fitting.

Based on these considerations, in this paper we endeavor to develop a model of distributed fracturing of rock masses, and the attendant permeability enhancement thereof, based on an *explicit micromechanical construction* of connected patterns of cracks, or faults. The material model is particularly suitable to model triaxial compression, i.e., stress states characterized by three compressive eigenvalues, where the formation of a localized single crack is very unlikely. We refer to such stress states, expressed in terms of total stresses, as overall compressive states or all-round compression states. The approach extends the linear kinematics multi-scale brittle damage material model introduced in De Bellis et al. (2016), adding the finite kinematics of a purely mechanical damage model (Pandolfi et al., 2006). In contrast to abstract damage mechanics, the fracture patterns that form the basis of the theory are *explicit* and the rock mass undergoes deformations that are compatible and remain in static equilibrium down to the micromechanical level. The fracture patterns are not arbitrary: they are shown in Pandolfi et al. (2006) to be optimal as regards their ability to relieve deviatoric stresses, and the inception, orientation and spacing of the fractures derive rigorously from energetic considerations. Following inception, fractures can deform by frictional sliding or undergo opening. The extension of the theory presented here additionally accounts for fluid pressure by recourse to Terzaghi's effective stress principle. When the fluid pressure is sufficiently high, existing fractures can open, thereby contributing to the permeability of the rock mass. By virtue of the explicit and connected nature of the predicted fractures, the attendant permeability enhancement can be estimated using simple relations from standard lubrication theory (Parsons, 1966; Snow, 1965; 1969), resulting in a fully-coupled hydro-mechanical model.

Experimental evidence shows that rocks, and brittle materials in general, become more ductile under high confinement (Chen and Ravichandran, 1996b; 2000; Pandolfi et al., 2006). Faulting structures characterized by localized large deformations are observed rather frequently in deep rocks undergoing high confinement. In the simulation of boundary value problems, the finite kinematics porous brittle damage model is able to capture very complex deformation mechanisms, where large deformations occur in narrow and localized zones of a rock formation, even though the remainder of the mass undergoes small deformations. Such a feature confers a prominent advantage to the present model with respect to the linearized one (De Bellis et al., 2016).

The paper is organized as follows. We begin in Section 2 with illustrating the hydromechanical framework, recalling the basic equations and the Terzaghi's effective stress principle, as an extension of the linearized model presented in De Bellis et al. (2016). In Section 3 we summarize the main features of the dry material model developed in Pandolfi et al. (2006), and modify the original formulation by introducing the pressure dependent behavior at fault inception. In Section 4 we derive analytically the permeability tensor associated to the presence of faults in the brittle damage material model. In Section 5 we validate the material model by means of comparison with experimental results taken from the literature, and demonstrate the applicability of the material model in the solution of boundary value problems by means of finite elements.

2. Hydro-mechanical framework

In porous media saturated with freely moving fluids, deterioration of mechanical and hydraulic properties of rock masses and subsequent problems are closely related to changes in the stress state, formation of new cracks, and increase of permeability. In fully saturated rocks, fluid and solid phases are fully interconnected and the interaction between fluid and rock is characterized by coupled diffusion-deformation mechanisms that confer a time-dependent character to the mechanical properties of the system.

The two governing equations of the coupled problem are the linear momentum balance and the continuity equation (mass conservation). The corresponding unknown fields are the solid displacements and the rate of fluid volume per unit area. Hydro-mechanical coupling arises from the influence of the mechanical variables (stress, strain and displacement) on the continuity equation, where the primary variable is the fluid pressure, and from the influence of the hydraulic variables (pore pressure and seepage velocity) on the equilibrium equations, where the primary variables are the displacements.